Differential photoconductive sampling with a resolution independent of carrier lifetime

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We present a novel approach to photoconductive sampling with a resolution which is virtually independent of the carrier lifetime and is governed solely by the circuit-limited gap charging time. Using photoconductors with a carrier lifetime of 150 ps, accurate measurement of a 65-ps-wide electrical signal is demonstrated and the actual resolution is believed to be 10 ps.

The development of picosecond/femtosecond mode-locked lasers over the last decade has resulted in several techniques for measuring ultrafast electrical signals with picosecond and even subpicosecond resolution. Most notable of these have been photoconductive sampling[1] and electro-optic sampling.[2] The electro-optic techniques have been the most successful in terms of the temporal resolution achieved (<1 ps, Ref. 3) since this tends to be limited only by the transit times of electrical or optical signals across circuit dimensions which are typically <1 mm and often as small as 10 μm. While photoconductive sampling offers very good sensitivity, its resolution has been constrained by the lifetime of photogenerated carriers. Best efforts to reduce these lifetimes have typically resulted in decay times of 2–10 ps,[4–6] with subpicosecond lifetimes only achieved in heavily damaged layers of silicon-on-sapphire.[7] In this letter, we present a novel approach to photoconductive sampling with a resolution which is virtually independent of the carrier lifetime. We call this technique "differential sampling" being similar in concept to previously reported differential techniques to improve the temporal performance of photoconductors when used as detectors[8] and as pulse generators.[9]

We start by considering the result of a general sampling measurement which can be expressed as

$$v_{\text{meas}}(\tau)=\int_{-\infty}^{\infty} v_{\text{sig}}(t) f_{\text{samp}}(t-\tau)dt, \qquad (1)$$

where v_{meas}, v_{sig}, and f_{samp} are the measurement result, the signal to be measured, and the sampling function, respectively. All three generic signals without any implication as to their nature (i.e., voltage, current, etc.). The conventional approach to sampling relies on f_{samp} being sufficiently short temporally to be considered a delta function, in which case v_{meas} is a direct representation of the signal v_{sig}. In the usual model of a photoconductive sampler, the sampling window rise and decay times are limited by two processes[10]: (1) the circuit limited time to charge the gap capacitance and (2) the decay of the gap photoconductivity through the recombination of excess carriers. For ordinary bulk semiconductors, carrier recombination clearly limits the sampling resolution with typical recombination times of ~ 100 ps to ~ 1 ns while the gap charging time is typically a few picoseconds. Consequently, there has been a great deal of effort in recent years to reduce carrier recombination times, usually by techniques such as ion bombardment, which, unfortunately, also tend to reduce the material quality.

As an alternative we reconsider the use of a photoconductor with a very long carrier recombination time. Since f_{samp} still has a fast rise time, the sampling result $v_{\text{meas}}(\tau)$ can be approximated by the integral of $v_{\text{sig}}(t)$ from τ to infinity and a derivative operation should recover v_{sig}. This can be expressed as sampling with a new effective sampling function as follows. Differentiating Eq. (1) yields

$$\frac{dv_{\text{meas}}(\tau)}{d\tau}=\int_{-\infty}^{\infty} v_{\text{sig}}(t)\left(\frac{df_{\text{samp}}(t-\tau)}{d\tau}\right)dt, \qquad (2)$$

which is just equivalent to sampling with the function $-df_{\text{samp}}(t)/dt$. In practice, we often use a finite difference which leads to

$$v_{\text{meas}}(\tau)-\alpha v_{\text{meas}}(\tau+\Delta\tau)=\int_{-\infty}^{\infty} v_{\text{sig}}(t)\{f_{\text{samp}}(t-\tau) - \alpha f_{\text{samp}}[t-(\tau+\Delta\tau)]\}dt, \qquad (3)$$

where α is a constant to be discussed below. The result is then equivalent to sampling with a new effective sampling function defined as

$$f_{\text{eff}}(t)=f_{\text{samp}}(t)-\alpha f_{\text{samp}}(t-\Delta\tau). \qquad (4)$$

Assuming f_{samp} has a fast rise time and a slow decay, then for short $\Delta\tau$, f_{eff} will consist of a sharp "spike" followed by a long negative tail of equal area (if $\alpha=1$). The initial "spike" is the desired sampling feature and in the limit of very short $\Delta\tau$, the ultimate temporal resolution will be limited by the details of the leading edge of f_{samp}. The negative tail, on the other hand, will lend a long-time limit to the resolution since signals much longer than the tail will generate no net sampled signal. It is helpful to consider that for an exponential decay of f_{samp}, this tail is equivalent to high-pass filtering or ac coupling the signal with a single pole filter prior to a true measurement. While this effect may be undesirable, it is not too serious since for decay times of ~ 100 ps, commercial instruments could be used to measure the long-time features. It is also somewhat surprising that the reduction of this effect now favors a longer recombination time although this will adversely affect the sensitivity. Finally, for the special case where the decay of f_{samp} is a single exponential with time constant τ_{rec}, the negative tail can be eliminated altogether by setting the parameter α in Eq. (4) to $\alpha=\exp(-\Delta\tau/\tau_{\text{rec}})$. The function f_{eff} for this case is plotted in Fig. 1 for various values of the delay difference $\Delta\tau$. The original function f_{samp} used is the correlation of two exponentials, a gap charging transient and carrier decay, which is the simple model response of a photoconductive sampling gate. Time constants of 2 and 150 ps were chosen as representative of the gaps used in our experiments. As can be seen,

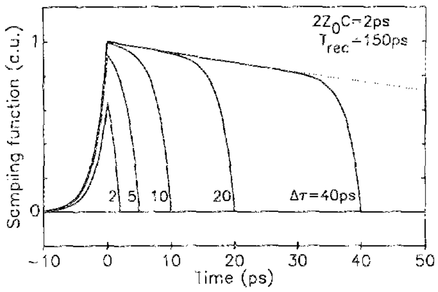
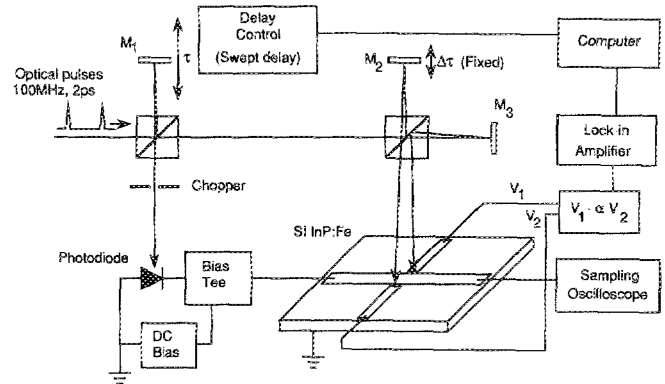


FIG. 1. Calculated effective sampling function f_{eff} for various values of the turn-on delay, $\Delta\tau$. The single photoconductor response, denoted by the dotted upper-envelope curve, is assumed to have a rise time of 2 ps and a decay time of 150 ps.



Experimental Set-up

FIG. 2. Experimental setup used for differential sampling measurement of a photodiode.

the sampling function is virtually independent of the recombination time and can be chosen with an arbitrary width down to the circuit rise time limit of 2 ps. The validity of this value may be questionable due to ground-plane reflections when using microstrip[3,4]; however, improvement to a coplanar geometry and capacitance-free "sliding contact"[11] should make even subpicosecond resolution achievable.

In order to implement the differential operation, we have tried three different schemes: (i) numerically shift and subtract the result of a single gap measurement from itself, (ii) modulation of τ by small amplitude sinusoid and synchronous detection of a single gap sampling signal at the modulation frequency, and (iii) simultaneous sampling by two photoconductors with a relative delay in turn-on times and subsequent real time subtraction of the results. While the first scheme is attractive in its simplicity, it is very sensitive to fluctuations in the average power of the mode-locked laser source. Since in a typical scan of τ, points separated by $\Delta\tau$ are measured several seconds apart in real time, this scheme is sensitive to laser fluctuations at frequencies of order 1 Hz. The second technique is similarly sensitive to laser power noise, *albeit* at the higher frequency used for the modulation of τ. This gives some improvement due to the usual roll-off laser power noise at higher frequencies. However, modulation of the delay τ usually involves mechanically dithering a mirror which is limited to ~ 100 Hz so improvement is only modest. Furthermore, care must be taken to ensure that only the delay τ is modulated without any accompanying scanning of the beam direction, since this can also generate a synchronous signal if the illuminated devices are sensitive to the position of the illumination spot. While the third scheme requires a certain degree of matching of the two photoconductors, we find it to be optimal in reducing the effects of laser source noise and we present results of this approach here.

The experimental setup used is diagrammed in Fig. 2. The electrical signal to be measured is fed to a microstripline which has opposing photoconductors in the same geometry as is often used for correlation measurements of photoconductors.[12] These photoconductors sample the signal with a relative delay in their turn-on times $\Delta\tau$, set by the positioning of mirror M_2. The correlation variable τ is then swept by moving mirror M_1. The low-frequency (~ 1 kHz) average currents from the two sampling electrodes are subtracted with the balancing factor α, and the result is synchronously detected with a lock-in amplifier. It is worth emphasizing that only the average currents are subtracted and not the high-speed waveforms themselves which would be a much more difficult task. Thus the effective sampling function of Fig. 1 is not physically realized anywhere in the circuit, but is only an artifact of the mathematical manipulation leading to Eq. (4). The simultaneous measurement of the two sampled signals means that fluctuations due to laser power noise are correlated for the two signals. Thus, for example, a 1% rms noise in a single gap signal translates to only a 1% rms noise level in the difference signal as well. Of course this is not true for all sources of noise in the measurement.

The center microstripline and two sampling electrodes (AuGe:Au) were designed for 50 Ω impedance and were separated by 50 μm gaps which had a dark resistance of 80 MΩ. The minimum on-state resistance was > 500 kΩ so the signal is virtually unaffected by the sampling action of the two photoconductors. The substrate was ordinary semi-insulating InP:Fe($\simeq 300$ μm), chosen to reduce surface recombination which tends to cause a nonexponential carrier decay.[13] A mode-locked dye laser operating at 100 MHz, $\lambda = 600$ nm, and a pulse width of 2 ps illuminated the photoconductors as well as a *pin* photodiode which generated the electrical signal.

The result of a differential sampling measurement of the *pin* photodiode is shown in Fig. 3(a). A sampling oscilloscope measurement of the same signal is shown in Fig. 3(b) which confirms the signal shape and calibrates the amplitude with a peak signal level of 60 mV. The resolution is believed to be a little over the fixed delay, $\Delta\tau$, which is 10 ps, although it is unfortunately not demonstrated here, presumably due to the lack of fast features in the measured signal. This is a substantial improvement over the single gap capabilities which had a photoconductive decay of 150 ps. Also, the average optical power incident on each gap was only 5 μW which is quite low for typical optoelectronic sampling.

In addition to the temporal resolution, an important aspect of any sampling system is its sensitivity. Ordinarily, such a differential scheme would be expected to suffer in this regard since the measurement result is only a small fraction of the signal which is actually measured. Nevertheless, this technique remains quite competitive with techniques which rely on high defect densities to reduce the carrier lifetime

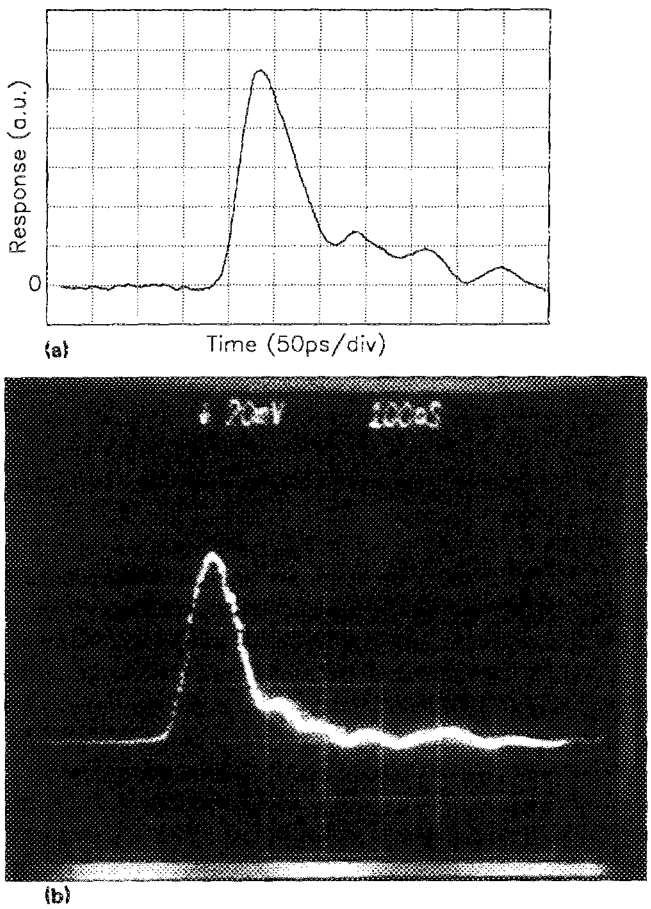


FIG. 3. (a) Differential sampling measurement result of the pulse response of a *p-i-n* photodiode. (b) Sampling oscilloscope measurement of the same signal confirming the measured pulse shape.

since these are usually accompanied by a significant reduction in mobility. The use of ion bombardment also often reduces the dark resistance of the photoconductor unless care is taken to compensate the doping of injected ions. Furthermore, the differential scheme offers the capability to easily trade-off resolution for sensitivity by simply increasing $\Delta\tau$. While such a trade-off is also possible with fast recombination photoconductors, its implementation would require a separate sampler for each temporal resolution, as well as careful characterization and control of the recombination enhancing mechanism. In the differential scheme presented here, $\Delta\tau$ is continuously varied by simply moving mirror M_2.

In conclusion, we have presented a new approach to photoconductive sampling which achieves a resolution which is independent of carrier lifetime and governed solely by the circuit limited time to charge the gap capacitance. The technique is more general, being applicable to any situation where a given sampling function is significantly asymmetric with respect to its rise and fall times. Accurate measurement of a 65 ps signal was demonstrated using photoconductors with $1/e$ decay times of ~ 150 ps. Determination of the actual resolution is currently being investigated and is expected to be < 10 ps. Further improvement is also expected with the use of a coplanar geometry.

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[1]D. H. Auston and P. R. Smith, Appl. Phys. Lett. **41**, 599 (1982).
[2]J. A. Valdmanis, G. Mourou, and C. W. Gabel, Appl. Phys. Lett. **41**, 211 (1982).
[3]J. A. Valdmanis and G. Mourou, IEEE J. Quantum Electron. **QE-22**, 69 (1986).
[4]P. M. Downey and B. Schwartz, Appl. Phys. Lett. **44**, 207 (1984).
[5]P. M. Downey, J. E. Bowers, C. A. Burrus, F. Mitschke, and L. F. Mollenauer, Appl. Phys. Lett. **49**, 430 (1986).
[6]R. Loefe, A. Schaelin, H. Melchior, and M. Blaser, Appl. Phys. Lett. **52**, 2130 (1988).
[7]M. B. Ketchen, D. Grischkowsky, T. C. Chen, C. C. Chi, I. N. Duling, and N. J. Halas, Appl. Phys. Lett. **48**, 751 (1986).
[8]W. Margulis, U. Österberg, B. Stoltz, A. S. L. Gomes, and W. Sibbett, Opt. Commun. **54**, 171 (1985).
[9]Y. Hori, J. Paslaski, M. Yi, and A. Yariv, Appl. Phys. Lett. **46**, 749 (1985).
[10]D. H. Auston, IEEE J. Quantum. Electron. **QE-19**, 639 (1983).
[11]D. R. Grischkowsky, M. B. Ketchen, C.-C. Chi, I. N. Duling, III, N. J. Halas, J.-M. Halbout, and P. G. May, IEEE J. Quantum Electron. **QE-24**, 221 (1988).
[12]D. H. Auston, A. M. Johnson, P. R. Smith, and J. C. Bean, Appl. Phys. Lett. **37**, 371 (1980).
[13]K. K. Li, J. R. Whinnery, and A. Dienes, in *Picosecond Optoelectronic Devices*, edited by C. H. Lee (Academic, New York, 1984), p. 195.